

Flight Validation of On-Demand Operations: The Deep Space One Beacon Monitor Operations Experiment

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ABSTRACT

The Beacon Monitor Operations Experiment is one of twelve new technologies currently being flight validated on NASA's Deep Space One mission. The technology enables a spacecraft to routinely indicate the urgency of ground contact using a tone signal rather than telemetry while also summarizing onboard data until a telemetry downlink is required. The two subsystems (tone communication and onboard summarization) have been deployed on DS1 and are in the final stages of flight-testing. The system can be used by missions to lower operational cost and in some instances to decrease mission risk. NASA will see a measurable unburdening of the antenna network if several missions use the technology. This paper provides a description of the technology and shares the results to date.

1.0 INTRODUCTION

The budget environment that has evolved since the advent of NASA's Faster, Better, Cheaper initiative has caused mission risk policies and mission designs to change in ways that have been conducive to the inception of new operations concepts and supporting technologies. Such was the case when the beacon monitor concept was conceived to enable a mission to Pluto to be achieved within the budget constraints passed down from NASA. The technology was accepted into the New Millennium Program and baselined for flight validation on the Deep Space One Mission. As the technology was being developed for DS1, the NASA community has expressed a growing interest and acceptance of adaptive operations and onboard autonomy.

In traditional mission operations, the spacecraft receives commands from the ground and in turn transmits telemetry

in the form of science or engineering data. With beacon monitoring, the spacecraft sends a command to the ground that instructs the ground personnel how urgent it is to track the spacecraft for telemetry. There are only four such commands. Thinking of beacon operations in this way creates a paradigm shift over the way we traditionally approach operations. Also, it is very important to not think of the tone message as just a little bit of telemetry. If one does this, it is easy to make the argument that a little more telemetry is better. Our approach is one where telemetry is only transmitted when it is necessary for ground personnel to assist the spacecraft or otherwise very infrequently if the spacecraft is fortunate enough to go long periods (a month or so) without requiring ground assistance. When telemetry tracking is necessary the intelligent data summaries contain the most relevant information to provide full insights into spacecraft activities since the last contact. The key challenge has been to develop an architecture that enables the spacecraft to adaptively create summary information to make best use of the available bandwidth as the mission progresses such that all pertinent data is received in one four to eight hour telemetry pass.

2.0 DS1 BMOX SUBSYSTEMS

It was required that two subsystems be designed and developed to implement the desired functionality for the DS1 experiment. These are, in fact, standalone innovations. Although they are being presented here primarily in support of cruise phase operations, there has also been interest in applying these technology components to other domains. Other potential applications include using in-situ beacons at Mars, adapting tone messaging and summarization to earth orbiters, using beacons for science event detection and notification, and in utilizing the tone system to reduce mission risk due to spacecraft operability constraints.

2.1 TONE SYSTEM

There are four tone signals and each uniquely represents one of the four urgency-based beacon messages. The DS1 tone definitions are summarized in Table 2.1.1. These tones are generated as the spacecraft software reacts to real-time events.

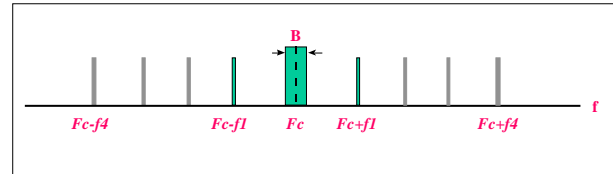
Table 2.1.1
Tone Definitions

Tone	Definition
Nominal	Spacecraft is nominal, all functions are performing as expected. No need to downlink engineering telemetry.
Interesting	An interesting and non-urgent event has occurred on the spacecraft. Establish communication with the ground when convenient. <u>Examples</u> : device reset to clear error caused by SEU, other transient events.
Important	Communication with the ground needs to be achieved within a certain time or the spacecraft state could deteriorate and/or critical data could be lost. <u>Examples</u> : memory near full, non-critical hardware failure.
Urgent	Spacecraft emergency. A critical component of the spacecraft has failed. The spacecraft cannot autonomously recover and ground intervention is required immediately. <u>Examples</u> : PDU failure, SRU failure, IPS gimbal stuck.
No Tone	Beacon mode is not operating, spacecraft telecom is not Earth-pointed or spacecraft anomaly prohibited tone from being sent.

Urgent Beacon tones on DS1 are sent when the spacecraft fault protection puts the spacecraft in standby mode. This condition occurs when the fault protection encounters a fault that it cannot correct. Standby mode halts the current command sequence, including IPS thrusting. During the DS1 tone experiment, the Beacon tone can be sent regularly at a prescheduled time, i.e., 30 to 60 minutes per day. The tone cannot be operated continuously because DS1 requires as much power as possible for IPS thrusting and the tone transmission uses some of the thrusting power. Routine operational use of the beacon monitor system is currently being explored for the DS1 extended mission, scheduled to begin in September of 1999.

It is important to communicate the urgency of ground response using a telecommunications method that has a low-detection threshold and short detection times. Ease of detection translates to lower cost operations. The signal structure is shown in Figure 2.1.2. Each message is represented by a pair of tones centered about the carrier frequency. Tones are generated by phase-modulating the

RF carrier by a squarewave subcarrier using a 90 degrees modulation angle. The carrier (f_c) is completely suppressed. The resulting downlink spectrum consists of tones at odd multiples of the subcarrier frequency above and below the carrier. Four pairs of tones are needed to represent the four possible messages.



B =Frequency uncertainty f_c =Carrier frequency
 f_i =Subcarrier frequency for the i^{th} message

Figure 2.1.2
Tone Signal Structure

The goal is to reliably detect the monitoring messages with zero dB-Hz total received signal-to-noise-spectral-density ratio (Pt/No) using a 1000 second observation time. Future missions are assumed to carry a low-cost auxiliary oscillator as a frequency source, instead of a more expensive, ultra-stable oscillator. The downlink frequency derived from the auxiliary oscillator is not precisely known due to frequency drifts caused by on-board temperature variations, aging, and uncorrected residual Doppler frequency. In addition, the downlink frequency also exhibits short-term drift and phase noise. These factors were taken into consideration in the design of the monitoring signal detector.

2.2 ONBOARD SUMMARIZATION SYSTEM

If the beacon tone indicates that tracking is required, the onboard summarization system provides concise summaries of all pertinent spacecraft data since the previous contact. The summarization system performs three functions: data collection and processing, mission activity determination, and episode identification. The data collection subroutine receives data from the engineering telemetry system via a function call and applies summary techniques to this data, producing summary measures for downlink to the ground. The mission activity subroutine determines the overall spacecraft mode of operation. This determination is used to choose the appropriate data and limits monitored by the episode subroutine. The mission activity is intended to be exclusive. When a new mission activity starts, the previous mission activity is assumed to have ended. The episode subroutine combines summary and engineering data received internally from the data collection subroutine

with the mission activity received from the activity subroutine and compares the data with mission activity specific alarm limits. It is necessary to use the mission activities to determine which data to use for episode identification and to identify the limits of these data. If the limit is exceeded, the subroutine spawns a new episode and collects past relevant data from the data collection subroutine. The past data collected will be one-minute summaries that go back in time as far as the user has defined. (So a five-minute episode would contain summaries starting five minutes before the episode to five minutes after the episode.) At the end of the episode, the subroutine outputs data to the telemetry subsystem for downlink.

Three different types of summarized data are produced onboard: overall performance summary, user-defined performance summary, and anomaly summary. Six different telemetry packets have been defined to contain this information. (See Figure 2.2.1) Taken as a whole, the telemetry packets produce summary downlinks that are used to enable fast determination of spacecraft state by ground personnel. The performance summaries are generated at regular intervals and stored in memory until the next telemetry ground contact. They are computed by applying standard functions, such as minimum, maximum, mean, first derivative, and second derivative, to the data. User-defined summary data can provide detailed information on a particular subsystem and are created at the user's discretion. Anomaly summary data (episodes) are created when the raw and summarized data violate high or low limits. These limits are determined by the subsystem specialist and stored in a table on-board the spacecraft. The limit tables are based on the current mission activity.

Figure 2.2.1
Summarization Telemetry Packets

Telemetry Name	Description	Output Frequency
Activity	Current value of mission activity	Output on change
Data Sample	Records a snapshot of every raw and summarized data channel	Regular interval, i.e., 15 min.
Episode Summary	Records general data about an out-of-limits data condition called an "episode"	One per episode
Episode Channel	Records specific data about a single data channel's behavior during an episode	One or more per episode
Tone Change	Current state of the beacon tone	Output on tone change
Channel Summary	Summary data about a single data channel's behavior since the last downlink	One for each channel out of limits
User Summary	A user-specified packet containing raw and/or summarized data	Duration user-specified

The software also has the capability to use AI-based envelope functions instead of traditional alarm limits. This

system, called ELMER (Envelope Learning and Monitoring using Error Relaxation), provides a new form of event detection will be evaluated in addition to using the project-specified traditional alarm limits. Envelope functions are essentially adaptive alarm limits learned by training a neural network with nominal engineering data. The neural net can be onboard or on the ground. For DS1, envelope functions are trained on the ground and then uploaded to the spacecraft. DS1 spacecraft fault protection will only be based on project-specified static alarm limits but the summary data can be generated based on the adaptive limits.

3.0 BEACON GROUND VISUALIZATION
SOFTWARE (BeaVis)

BeaVis is a ground-based visualization environment for viewing summary data and tone state histories. The tool was designed to facilitate quick interaction with data that has been summarized in a remote system. Summary data files (as downlinked telemetry for space missions) contain all of the important information since the last contact. While it is possible that the summary information is just providing confirming status information, for an adaptive or autonomous system there is likely some urgency in understanding the data because it would not have been sent in the first place if the remote system was functioning normally. For this reason, it was imperative that we design a system that would enable an operator to quickly evaluate summary data to arrive at the correct diagnosis of system behavior. The burden here is shared between the remote system's ability to summarize and the ground system's ability to present the information logically to the user.



Figure 3.1
BeaVis Timeline Display

The BeaVis delivery for DS1 provides several novel ways of visualizing summary information and includes a timeline display, tabular displays and strip charts. The timeline display, shown in Figure 3.1, provides access to summary downlink data and indicates beacon tone detections that have transpired during the mission. The

tabular and strip chart displays can be accessed via "hypertext" style links from the timeline display. There are GUI elements that show specific summary data components, such as mission activity changes, snapshot telemetry, episode data and user summary data. The environment also includes a tool for creating the parameter tables that are uploaded to the spacecraft.

4.0 EXPERIMENT RESULTS TO DATE

Results so far are showing that the system is performing on par with expectations and functional validation is approximately 90% complete. Validation is defined as functional deployment and means that the system is operational and basically checked out. Full analysis of results is not included as validation by the mission's definition. After the next software upload, currently scheduled to occur in June of 1999, BMOX software will be executed fully. The experiment should reach 100% validation by July 1, 1999. We will continue to conduct the experiment after being fully validated in order to provide data required for performance analysis. Performance evaluations, though still ongoing are yielding some interesting results.

4.1 TONE SYSTEM PERFORMANCE

To date, a total of twelve tone experiments have been conducted. Ten of these experiments were purely tone experiments designed to check out the functionality and characterize the performance of the tone transmission, detection, and delivery systems. These experiments are called Xtone or Ktone experiments for X-band and Ka-band respectively. For these activities, a pre-selected tone (subcarrier) or a sequence of tones was uploaded to the spacecraft prior to the experiment. The tone detection team did not know the tone sequences. During the experiment, the spacecraft commanded the transponder to transmit the tone (or tones) as sequenced. The tone detector at NASA's Goldstone antenna complex, operated remotely from JPL, detected the transmitted tones in near real-time and reported the detection results to various recipients via Email. A total of ten such experiments were scheduled, two of which were not executed because of DS1 schedule changes. Of the eight experiments conducted, six were completely successful and two were deemed partially successful. One of the six successful experiments was a Ktone pass. While data is still being analyzed, preliminary post-pass analysis has validated the correct operation of the tone transmission, detection, and delivery systems. Based on preliminary Xtone detection results, the tone detector appears to have achieved the goal of detecting the signal at 5 dB-Hz. The other two experiments were conducted in conjunction with beacon flight software

experiments, known as Btransmit, where the onboard beacon software analyzes spacecraft engineering data and selects the tone for transmission. Both of these experiments were completely successful.

The signals used for beacon monitor are characterized by three things: (1) the signal strength can be extremely low, (2) the initial tone frequencies, which are derived from an on-board auxiliary oscillator, are not known exactly, and (3) the tone frequencies are constantly drifting. The tone detector is designed to detect these types of signals with a high-level of confidence. Based on data provided by the DS1 telecom personnel, the auxiliary oscillator temperature can undergo a wide range of changes after an OPNAV (optical navigation) maneuver. This results in a very large frequency uncertainty and a very high rate of change (>6 Hz/sec), both of which could exceed the limits of the tone detector (when the signal level is low). A better understanding of the characteristics of the beacon signal in a flight environment (initial frequency uncertainty, drift rate, etc.) and how they affect the performance of the tone detector is being obtained as we complete analysis of the experiment data.

4.2 SUMMARIZATION PERFORMANCE

The end-to-end summarization system is 80% validated, or when weighted against the entire BMOX system, it is 40% out of 50% validated. Functional checkout of the data generation (onboard) and visualization software (ground) has been completed. A detailed performance analysis required to verify that the system is fully operational is ongoing and is 5% out of 15% completed. The tone selection software has been fully checked out.

The initial set of summarization data included 97 'engineering' sensor values sampled onboard once per second. These values were chosen by the Beacon Team based on their importance in detecting major spacecraft anomalies. Five additional sensor values were derived from the original set. Functions including minimum, maximum, mean, first derivative, and second derivative were applied to 16 of the original sensors. High and low limits were applied to 33 of the sensor values.

The data summarization component of beacon has detected several out-of-limit conditions. Several other sensor limit checks gave us false alarms that had to be updated. The ability to rapidly update our alarm limits was part of our validation objectives. We expected false alarms because our limits did not come from the flight team. The first phase of validation used limits from the Beacon Team to test the functionality of the software. The second phase of our validation involves getting limits from the subsystem experts. With more accurate limits, spacecraft engineers

should be able to use summarization data to successfully determine spacecraft anomalies. The data summarization software can provide enough detail for spacecraft engineers using the beacon ground visualization tools to respond appropriately.

One activity that is producing important results involves analyzing summary system performance on DS1 anomalies to date. Although ELMER will not be fully deployed until the next software upload, preliminary results when running ELMER on historical data are showing that adaptive alarm thresholds can track gradual trending of sensor data much tighter than the current DS1 static alarm limits. We see this in monitoring the gradual drift in eight solar array temperatures sensors, one of which is shown in Figure 4.2.1. In comparing traditional limits with ELMER limits during the 81 days of operations, we see that ELMER limits track actual spacecraft performance much more precisely than static limits, which would be off the scale of this chart.

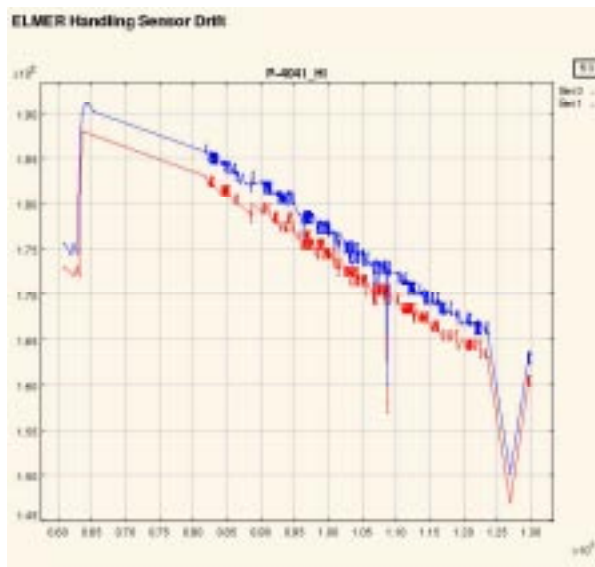


Figure 4.2.1
Tracking of adaptive alarm limit to
DS1 solar array temperature

Another validation exercise is confirming that summarization can capture subtle, yet important spacecraft episodes. In ground tests, ELMER detected an unexpected heater turn-on that occurred when the solar panels went off-axis during a spacecraft maneuver. Since ELMER trains across multiple parameters using nominal data, the summarization system detected this event without explicit a priori knowledge of the scenario. This data is shown in Figure 4.2.2.

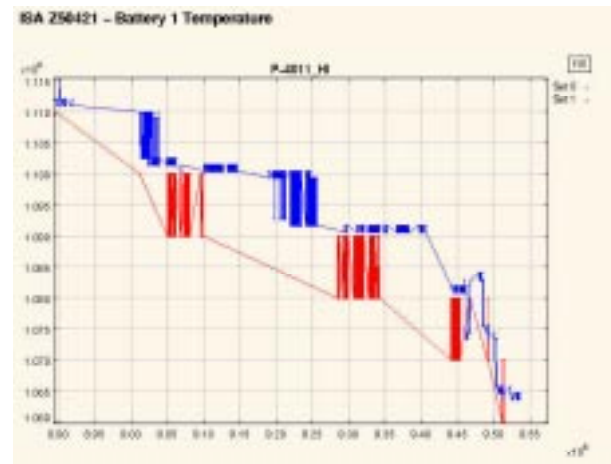


Figure 4.2.2
Battery Temperature Episode Detection

We have already started gathering information from the subsystem engineers for the second phase of the beacon experiment scheduled to begin in June 1999. One of the inputs we have received from the flight team is to trigger limit checks based on a sensor value. For example, start monitoring battery voltage when the battery current is greater than 10A. We will consider adding this capability in the future. The summarization software already has context dependent limit checking, but it uses the overall spacecraft activity, not just the state of one component.

4.3 OPERATIONAL EFFECTIVENESS

The utilization of the ion propulsion system (also called solar-electric propulsion) on DS1 offers an additional justification for baselining beacon operations. The IPS provides continuous thrust for much of the cruise phase. The operational margin for IPS thrusting represents the duration for which IPS could be off and still allow the spacecraft to reach the target asteroid. Due to the low thrust associated with IPS and because actual thrusting did not start until several weeks after launch, the operational margin is only a few weeks. Telemetry downlink passes are becoming less frequent as the DS1 mission progresses. Eventually, there will only be one telemetry pass per week. If the spacecraft experiences a problem that requires the standby mode, the IPS engine will be shut down. It could be up to one week before the flight team has visibility to that standby mode. Using the beacon tone system during the periods between scheduled telemetry downlinks can be a cost effective way to decrease mission risk because it reduces the likelihood of losing thrusting time and not making the intended target. Other future IPS missions have taken note of this fact and are interested in beacon tone services to lower their mission risk.

5.0 LESSONS LEARNED IN DEVELOPMENT

The DS1 flight software was redesigned about eighteen months before launch. This decision greatly compacted an already tight development schedule. As a result, the testing of all non-essential software functions was delayed until after launch. The beacon experiment was considered a non-essential piece of software and therefore was only tested pre-launch for non-interference with the other flight software. In post launch testing, routine software problems were found that had to be corrected before turning on beacon software. A nominal amount of system testing prior to launch would have likely prevented these problems from delaying activation of the software and would have decreased development cost.

Before the software redesign, the beacon software was tightly integrated with the DS1 fault protection software. The decision was made after the redesign to de-couple the two pieces of software. Previously, the fault protection monitors triggered the beacon tones. After the redesign, the mapping of faults to tones was performed using two different methods. All spacecraft standby modes are now mapped to the urgent beacon tone. The interesting and important beacon tones are mapped using beacon software determined limits. Decoupling the fault protection software from the beacon software gives us maximum flexibility to determine what sensors to monitor. It is unfortunate, however, that our algorithms for determining faults are not nearly as sophisticated as the fault protection monitors. These monitors can look at many different values based on conditional logic before determining what fault has occurred. Complete integration with fault protection would have created a more powerful system.

6.0 FUTURE WORK

There are three facets to future work in this area. One thrust is the operational concept. DS1 BMOX is the first major implementation of the components required to achieve adaptive operations on a space mission. Work in this area is expected to continue since beacon operation is baselined for the missions in the JPL Outer Planets Program. Currently, this involves missions to Europa and Pluto scheduled for launch in the next few years. The operational concept can also be extended to implement a science beacon for increased science return and to provide innovative ways to lower the cost of earth-orbiter operations. A second area for future work is in low-cost telecommunications systems for weak signal detection. Today's faster, better, cheaper spacecraft are also often operationally constrained. Providing a weak signal detection service (i.e. a pager service) for these missions is likely to be useful in many ways that we can't even anticipate currently. We say this given the many

suggestions that we have received to date on how such a service could be utilized on DS1 and other missions at JPL. The third area for future work is in onboard data summarization. DS1 BMOX is the first major effort at JPL to put summarization techniques onboard a spacecraft. This is likely the first step in a roadmap for developing a myriad of summarization technologies to provide a diverse mission set with the tools necessary to capture the most important data for downlink.

7.0 ACKNOWLEDGEMENT

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